Peltier Thermoelectric Modules Modeling and Evaluation

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Abstract

The purpose of this work is to develop and experimentally test a model for the Peltier effect heat pump for the transient simulation in Spice software. The proposed model uses controlled sources and lumped components and its parameters can be directly calculated from the manufacturer's data-sheets. In order to validate this model, a refrigeration chamber was designed and fabricated by using the Peltier modules. The overall system was experimentally tested and simulated with Spice. The simulation results were found to be compatible with the experimental results. This model will help designers to better design thermal systems using the Peltier modules.

Keywords: Peltier Effect thermoelectric Heat Pumps; Heat sink; Spice Model.

1. INTRODUCTION

The Peltier effect thermoelectric heat pump is a semiconductor based electronic component that functions as a heat pump. Just by applying a low DC voltage to this module, one surface gets cold and the other surface gets hot. And just by reversing the applied DC voltage, the heat moves to the other direction. Thus this thermoelectric device works as a heater or a cooler.
The Peltier thermoelectric heat pumps have been used for medical devices [1,2], sensor technology [3,4], cooling integrated circuits [5], automotive applications and military applications.
This project is about the validation of a Spice model of the Peltier thermoelectric heat pump suitable for transient simulations. In order to verify this model, a cooling chamber was designed and fabricated. Its inside temperature was measured under different rates of input power and its performance was calculated. This Spice compatible model will help designers predict the thermal behavior of system using Peltier thermoelectric heat pumps.

2. PRINCIPLE OF OPERATION AND MODELING

The thermoelectric heat pump was discovered by a French watchmaker during the 19th century. It is described as a solid state method of heat transfer generated primarily through the use of dissimilar semiconductor material (P-type and N-type).

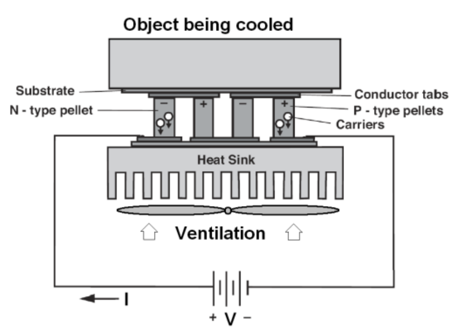

FIGURE 1: Peltier effect heat pump electrical and mechanical installation.

Figure 1 shows a Peltier effect heat pump typical mechanical and electrical installation. Like conventional refrigeration, Peltier modules obey the laws of thermodynamics. Basically the refrigerant in both liquid and vapor form is replaced by two dissimilar conductors. The solid junction (evaporator surface) becomes cold through absorption of energy by the electrons as they pass from the low energy level to the high energy level. The compressor is replaced by a DC power source that pumps the electrons from one semiconductor to another one. A heat sink replaces the conventional condenser fins, discharging the accumulated heat from the system. The following table outlines the differences and similarities between the thermoelectric module and the conventional refrigerator.

The evaporator	Allows the pressurized refrigerant to expand, boil and evaporate (The heat is absorbed during the change of state from liquid to gas)	At the cold junction, heat is absorbed by the electron as they pass from a low energy level (P-type) to a high energy level (N-type)
The compressor	Acts on the refrigerant and recompresses the gas to liquid. The refrigerant leaves the compressor as a vapor.	The power supply provides the energy to move the electrons
The condenser	Expels the heat absorbed at the evaporator to the environment plus the heat produced during compression into the ambient. Also, the refrigerant returns to the liquid phase.	At the hot junction, heat is expelled to the heat sink as the electrons move from high energy level to the low energy level

TABLE 1: Comparison between the conventional and the solid state refrigeration

The absorbed heat *qa*, the emitted heat *qe* and the input electrical power *P* used to operate the modules can be described from equations (1).The heat pumped is the sum of the Peltier effect term *(αm.T.I),* the heat conduction term *(ΔT/Θm)* and the Joule effect term *(I^2Rm).* It is conventional to leave out the effect of the Thompson phenomena because it is negligibly small. Additionally, it is common practice to apply equivalent electrical circuit scheme in one-dimensional heat transfer problems [7].

$$\begin{aligned} qa &= \frac{\Delta T}{\Theta m} + \alpha m.Ta.I - \frac{I^2Rm}{2} \\ qe &= \frac{\Delta T}{\Theta m} + \alpha m.Te.I + \frac{I^2Rm}{2} \\ P &= V.I = I(\alpha m.\Delta T + Rm.I) \end{aligned} \qquad (1)$$

Where: *Rm* is the resistance of the module, *αm* is the Seebeck-coefficient of the pn junction, *Θm* is the thermal resistance, *Te* is the absolute temperature of the heat emitted, *Ta* is the absolute temperature of the heat absorbed and $\Delta T = Te - Ta$. *qa* and *qe* represent the amount heat absorbed and emitted from the module. Finally, *V* and *I* are the voltage and the current from the input power supply. The Coefficient Of Performance, or COP in short, describes the efficiency of the heat pump when working in cooling and in heating modes. The COP is expressed by equations (2).

$$COP = qa / P \qquad (2)$$

2.1 Previous Models

Various equivalent circuits have been developed to model the behavior of the Peltier heat pump. The purpose of these models is to simulate the behavior of Peltier modules in CAD tools like Spice, and hence to predict the amount of heat that it can transfer. Figure 2 proposes a thermal network [6]. In this scheme, the Peltier effect is represented by the flow source $Ps = \alpha m.Tc.I$, the Joule effect by $P_{J/2} = Rm\, I^2/2$ and a thermal resistance term by $Rth = \Theta m$.

Figure 3 shows an equivalent circuit of the Peltier effect heat pump based on a Cauer-type network as it is described by [7]. Finally Figure 4 shows a proposed circuit from [8]. It consists of with two dependent sources instead of three and lumped parameters instead of distributed ones as described in previous model.

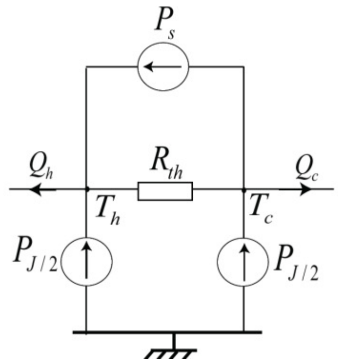

FIGURE 2 : Peltier effect model from [6].

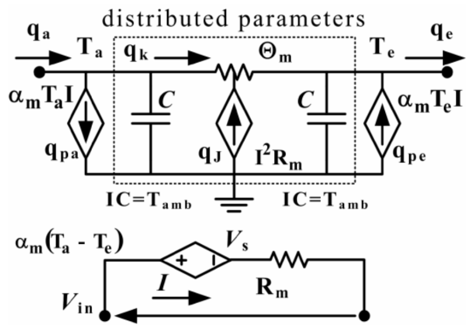

FIGURE 3 : The Equivalent Peltier from [7]

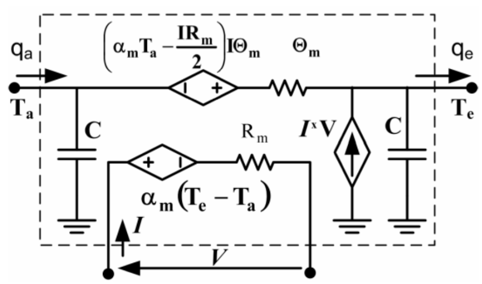

FIGURE 4 : The Equivalent Peltier from [8]

2.2 The Proposed Model

Figure 5 shows a modified equivalent circuit of the Peltier module. This model is made of two current dependent voltage sources, two current dependent current sources and two lumped parameters. It can be easily implemented on Spice since all the elements exist on its library.

The parameters *αm*, *Θm* and *Rm* can be directly calculated from the manufacturers data sheet according to equations (3).

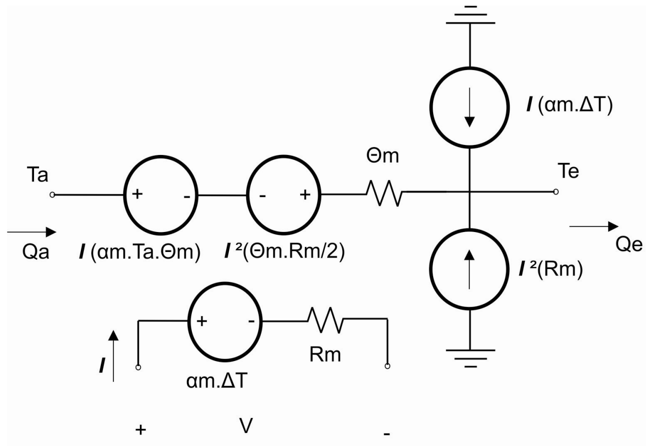

FIGURE 5: Proposed model of Peltier module.

$$Rm = \frac{Vmax}{Imax} * \frac{(Th - \Delta Tmax)}{Th}$$

$$\Theta m = \frac{\Delta Tmax}{Imax * Vmax} * \frac{2Th}{(Th - \Delta Tmax)} \qquad (3)$$

$$\alpha m = \frac{Vmax}{Th}$$

Where *ΔTmax* is the largest temperature differential that can be obtained with *Imax* and *Vmax*. *Th* being the temperature in the hot side.

3. EVALUATION OF THE PROPOSED MODEL

3.1. Design and Fabrication of a Refrigeration Chamber

The main body of the refrigeration chamber has a dimension of: 0.11x0.29x0.33 m^3 strongly insulated to minimize heat loss to the ambient air. In the cross section of this chamber, three layers exist: two walls of aluminum separated by an insulating material of 3 cm of thickness. Refer to figure 2.

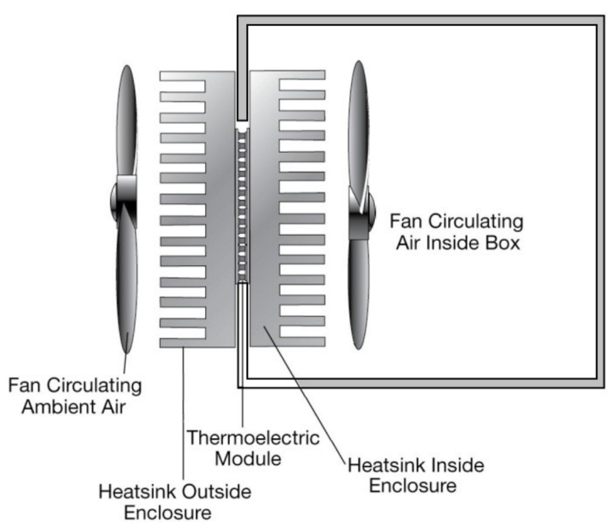

FIGURE 6: Main body of the refrigeration chamber

High density heat sinks were specially fabricated for this project. They are made of Aluminum and are 350 x 75 x 39 mm³, with 21 fins along their length and weight is 1500 Grams. Their specific heat is 0.963 J/g.°C. The "hot" surface of the thermoelectric heat pump must be attached to a heat sink that is a capable of carrying away both the heat pumped by the modules and the heat generated by the Joule effect.
The "cold" surface is also attached to another heat sink that will carry away the cold air, hence decreasing the temperature differential ΔT, and then making the thermoelectric more efficient.
A "spacer block" is also put between the modules and the heat sinks. Its thickness, of 18 mm, separates the "hot" heat sink from the "cold" one, which yields to a maximum heat transfer.
Peltier modules from Ferrotec [9] were used in this experiment. Their specifications are Imax=8.5A, Qmax=80W, Vmax=17.5V, DTmax=72°C.
Their thermal resistance, Seebeck coefficient and internal resistance were calculated according to equations (3). Rm = 1.6Ω, $Θm$ = 1.25 K/W and $αm$ = 0.054 V/K for Th = 300K.

3.2. Simulation of the Refrigeration Chamber

The equivalent circuit of the chamber was implemented on Spice according to figure 3. The lumped parameters R's and C's are defined as follows:

- R1: Thermal resistance of the chamber's wall
- R2, R5: Thermal resistance of the heat sink + fan
- R3, R4: Assembly's thermal resistance
- C3, C4: Heat capacity of alumina ceramic plates and pellets of the Peltier modules.
- C2, C5: Heat capacity of the heat sinks
- C1: Heat capacity of the chamber
- T_{SSHC}: Temperature inside the chamber
- Ta/Te: Cooling/Heating temperature at Peltier module
- Ta'/Te': Cooling/Heating temperature at Peltier module after assembly

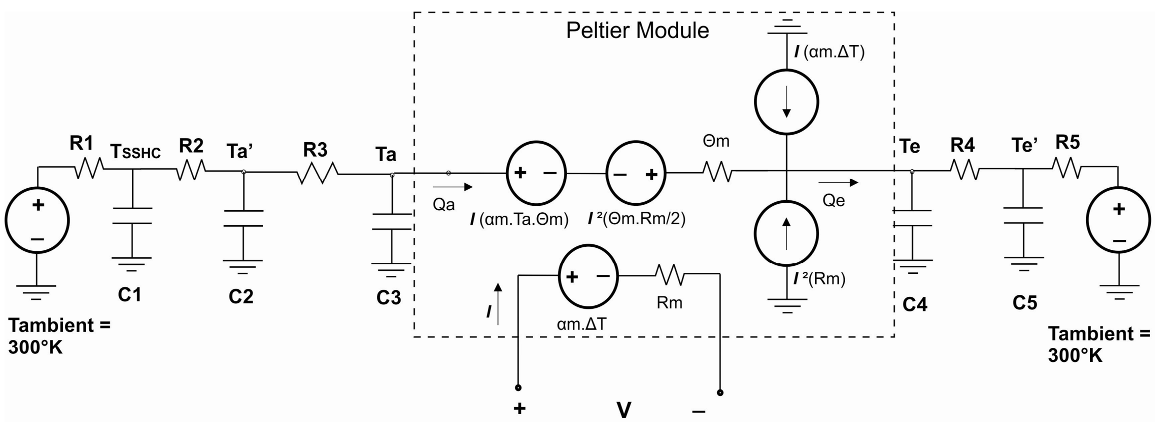

FIGURE 7: Spice equivalent circuit of the refrigeration chamber

3.3. Experimental Evaluation of Refrigeration Chamber

The thermal output power was calculated by using the laws of thermodynamics [10, 11, 12]:
Heat given by modules = [Heat gained by aluminum chamber + Heat gained by the air inside + Heat gained by heat sinks + Outside losses]. First order equations were used to calculate the *COP*. The outside losses are neglected at the beginning of the experiment when the temperature increases linearly with time.
Heat gained by the air: P(air)

$$P(air).dt = n.c'.dT \tag{4}$$

with:
P(air) : Output power (W)
n: Number of moles (0.4616 mole)

c': Molar heat capacity (20.93 j/mole.°K)
dt: t2 – t1 (sec)
Then: $P(air) = 9.65\ dT/dt\ (W)$

Heat gained by the chamber and the heat sinks: P(Aluminum)

$$H = m.c.dT \tag{5}$$

with
H: The gained energy (J)
m: Total mass (Chamber = 2200g, Heat sinks = 1875.75g) = 4048.75 g
c : Specific heat (0.963 J/g.°C for Aluminum)

$$P(Aluminum) = H / dt = 3908.6\ dT/dt$$

3.4. Experimental Results

The refrigeration chamber was run for many values of input current. The temperature, time and input electrical power were measured. The simulation and experimental results are shown in figure 4. The obtained COP for the different current is shown in table 3. The experimental results show a good fit of the Spice simulation with the experimental data.

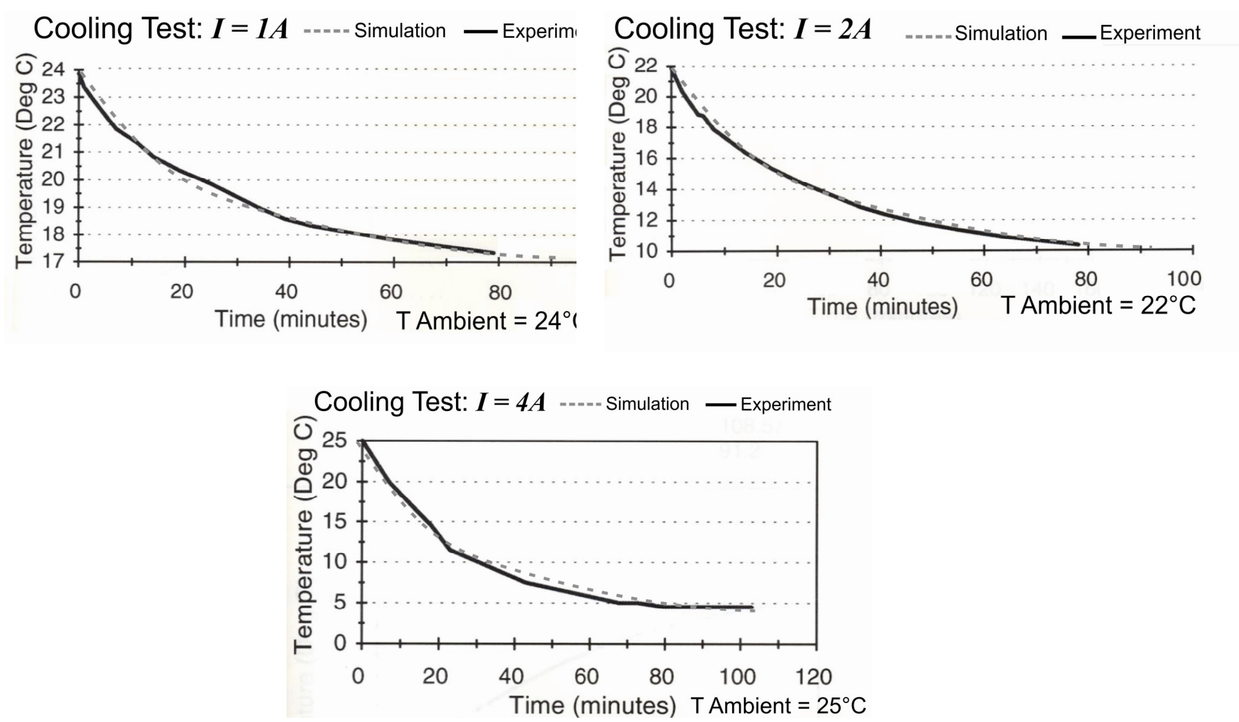

FIGURE 8: Simulation and Experimental Results for 1A, 2A and 4A Cooling

Input Current (A)	Input Power (W)	Output Power (W)	COP(Experimental)	COP(Simulation)
1	12.89	24.61	1.91	2.04
2	52.62	43.06	0.818	0.98
3	119.58	55.37	0.463	0.51
4	216.56	55.38	0.255	0.32

TABLE 2: Cooling Performance Results

4. CONCLUSION

A model has been developed to simulate the transient state for a Peltier thermoelectric module. This model uses controlled sources and lumped parameters, hence can be easily simulated with simulation software like Spice. The model parameters were calculated by using the manufacturer's datasheet.

In order to validate this model, a refrigeration chamber that uses Peltier modules was designed and fabricated. The overall system was tested and simulated with Spice under various values of input currents. The result is a good fit between the simulation and the experimental data.

This model can easily extended with lumped parameters R's and C's representing the thermal resistance and the heat capacity of a thermal system.

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